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Global Seasonal Climatologies of Ocean Chlorophyll: Blending *In situ* and Satellite Data for the CZCS Era

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Abstract. The historical archives of *in situ* (National Oceanographic Data Center) and satellite (Coastal Zone Color Scanner) chlorophyll data were combined using the blended analysis method of *Reynolds* [1988] in an attempt to construct an improved climatological seasonal representation of global chlorophyll distributions. The results of the blended analysis differed dramatically from the CZCS representation: global chlorophyll estimates increased 8-35% in the blended analysis depending upon season. Regional differences were even larger, up to 140% in the equatorial Indian Ocean in summer (during the southwest monsoon). Tropical Pacific chlorophyll values increased 25-41%. The results suggested that the CZCS generally underestimates chlorophyll. Regional and seasonal differences in the blended analysis were sufficiently large as to produce a different representation of global chlorophyll distributions than otherwise inferred from CZCS data alone. Analyses of primary production and biogeochemical cycles may be substantially impacted by these results.

1. Introduction

Satellite observations of ocean color provide large-scale, repeat coverage sampling of global ocean chlorophyll that are necessary to help understand the role of phytoplankton on biogeochemical cycling, climate change, and fisheries. However, remotely-sensed data are subject to several sources of error that affect their accuracy, for example, calibration, atmospheric correction algorithm errors, uncertainties in knowledge of the atmospheric optical state, and problems deriving chlorophyll from radiances. Conventional *in situ* methods (e.g., ships and buoys) typically provide high quality, accurate data, but can only produce extremely limited spatial observations due to the expense of sea operations and the large areal extent of the ocean. Thus, *in situ* data provide high quality chlorophyll information that satellites cannot, and satellites provide horizontal and temporal observations that *in situ* methods cannot. A blending of data sources can maximize the strengths of each data set and produce a high quality, large spatial, data set of ocean chlorophyll.

In this paper we combine *in situ* chlorophyll data from the extensive archive maintained by the NOAA/National Oceanographic Data Center (NODC) with remotely-sensed data from the Coastal Zone Color Scanner (CZCS) in an attempt to provide an enhanced set of seasonal climatologies. We utilize the Conditional Relaxation Analysis Method [*Oort*, 1983] that has been successfully applied to sea surface temperature (SST) data [*Reynolds*, 1988]. The advantage of this method is that it preserves the integrity of the *in situ* values while preventing the overwhelming of *in situ* data with the vastly larger number of observations by satellites, at the same time taking advantage of the spatial variability observed from the satellite.

We limit the analysis to the CZCS era (1978-1986) because of the availability of large amounts of *in situ* data (about 70,000 surface observations, or 54% of the total archive) and satellite data. The CZCS record represents the only multi-year satellite ocean color data set currently available to produce seasonal climatologies, since the Sea-viewing Wide Field-of-view Sensor has collected <2 years of data as of this writing and the Ocean Color and Temperature Scanner provided only 9 months of data in its abbreviated lifetime. Global primary production models [*Iverson et al*., 1999; *Behrenfield and Falkowski*, 1997; *Antoine et al.,* 1996] utilize climatological CZCS pigment data as a primary independent variable. Chlorophyll scales linearly and sometimes even non-linearly in these models, so it is important to provide enhanced estimates of global ocean chlorophyll in order to improve estimates of global primary production.

2. Methods

Blending of *in situ* and remotely-sensed data requires the availability of both sets of data. Our efforts emphasize the period 1978-1986 (the lifetime of the CZCS) because this condition is satisfied for this period. Blended chlorophyll data sets are 1^{o} by 1^{o} longitude/latitude gridded fields. Seasonal climatologies are constructed using Northern Hemisphere conventions: winter is January through March, spring is April through June, summer is July though September, and autumn is October through December.

2.1. *In situ* Data

In order to produce the highest quality blended data set, it is paramount to begin with high quality *in situ* data. *In situ* data were subjected to rigorous quality control procedures. These involved elimination of values with position or time problems (e.g., data on land), duplicate elimination, identification and correction of depth inversion problems, range checking over ocean basins, checks of descriptive statistics, and subjective elimination of systematically bad data points (e.g., an individual cruise) [*Conkright et al.*, 1998, *Conkright et al.*, 1994a,b]. The data were interpolated to standard levels using a 3- or 4-point Lagrangian interpolation [*Reiniger and Ross*, 1968]. We used unanalyzed 1^{o} by 1^{o} *in situ* chlorophyll mean values [*Conkright et al.*, 1998a] in the blended analysis.

2. 2. CZCS Data

Monthly mean CZCS pigment data (chlorophyll + phaeopigments) were obtained for each year during the lifetime of the CZCS mission from the NASA Goddard Space Flight Center/Distributed Active Archive Center (GSFC/DAAC). These data were produced at 1^{o} x 1^{o} resolution. CZCS pigment estimates were converted to chlorophyll by

$$\log_{10} S = \frac{(\log_{10} P00.127)}{0.983} \qquad (1)$$

O'Reilly et al., 1998] where S indicates satellite-derived chlorophyll and P indicates satellite-derived pigment. This relationship generally agrees with the constant adjustment factor provided by *Balch et al.* [1992], except that it accounts for the covariance of detrital materials (e.g., phaeophytin) with chlorophyll [*Gordon et al.*, 1988].

Seasonal climatologies were constructed by first combining chlorophyll estimates from the individual months into seasons for each year for which the CZCS was operating, and then averaging the seasons over the CZCS years. This enabled us to remove the sampling alias occurring in CZCS seasonal composites [*Feldman et al.*, 1989] due to unequal sampling of months within seasons.

2.3. Blended Analysis

In situ and satellite data were merged using the Conditional Relaxation Analysis Method (CRAM; [*Oort*, 1983]). This analysis assumes that *in situ* data are valid (after rigorous quality control), and uses these data directly in the final product. The satellite chlorophyll data were inserted into the final field using Poisson's equation

$$\nabla^2 C = \Psi \qquad (2)$$

where C is the final gridded field of chlorophyll, and Y is a forcing term, which is defined to be the Laplacian of the gridded satellite chlorophyll data (Ñ^{2}S). *In situ* data serve as internal boundary conditions, and were inserted directly into the solution field C

$$c_{ibc} = I \qquad (3)$$

where the subscript $_{ibc}$ indicates internal boundary condition and I is the *in situ* value of chlorophyll. Thus *in situ* data appear un-adjusted in the final blended product. *In situ* data were averaged over 3 x 3 grid points to reduce point-to-point disparities. Missing data and land were set to 0.

Modifications to the blended analysis are required for ocean chlorophyll. These are due to the wide range of

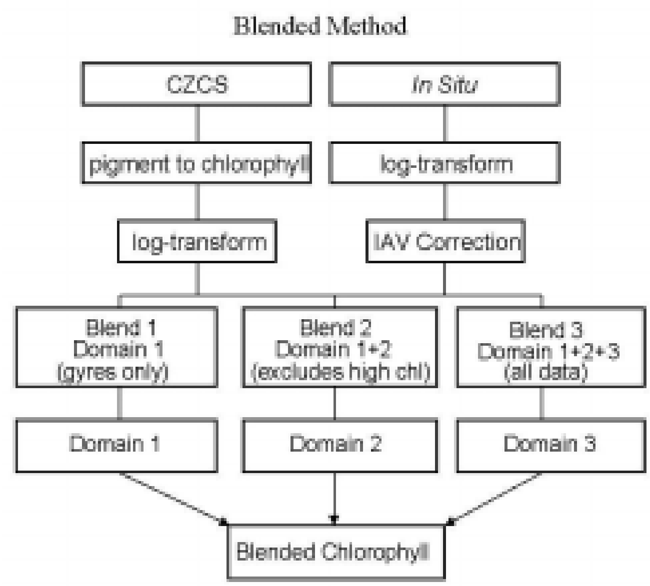

Figure 1. Flow path of the blended analysis procedure. CZCS data are first converted from pigment to chlorophyll, and log-transformed. In situ data are first log-transformed, and then an Inter-annual variability (IAV) correction is performed to reduce the effects of year-to-year mismatches between the CZCS and in situ data. Then the data are blended individually according to biomass domains. The final blended chlorophyll is produced by piecing together the results of the individual blended analyses according to the biomass domains.

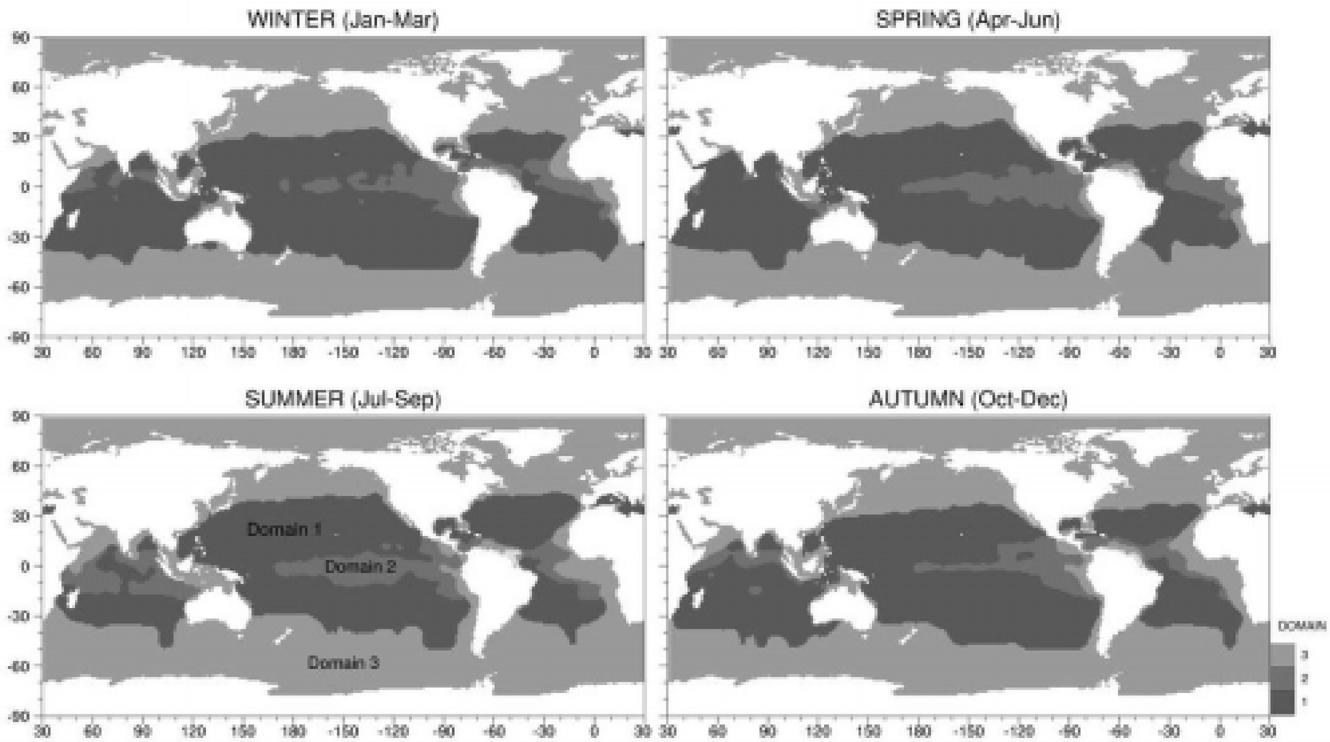

Figure 2. Seasonal chlorophyll biomass domains defined by CZCS abundance, that constrain *in situ* and satellite data blending. Domain 1 is the mid-ocean gyre region, Domain 2 is equatorial upwelling, Domain 3 indicates the high chlorophyll coastal, polar, and sub-polar regions. The open ocean gyres (Domain 1) are clearly distinguished from high abundance upwelling, coastal, and high latitude domains. Note the changes in the biomass domain dimensions and locations by season. Note also the seasonal expression of the Amazon/Orinoco plumes, which is delineated as a lighter shade of grey than Domain 3.

variability naturally occurring in chlorophyll distributions, and because of large amounts of inter-annual variability in the CZCS record, giving rise to mismatches between satellite and *in situ* observations. An overview of the modifications is illustrated in Figure 1.

Ocean chlorophyll can vary over three orders of magnitude. In the absence of sufficient data, *in situ* observations in the blended analysis can extend their influence across physical-biological-geographical domains, producing an unrealistic representation in the blended data set. These problems are not encountered with SST, for which the blended analysis method has traditionally been applied [*Reynolds*, 1988], because of the reduced range of variability of ocean temperature. Rigorous quality control methods and acquisition of new data have helped alleviate this problem. However, the best results are obtained by log-transforming both data sources prior to executing the analysis.

Some residual unrealistic cross-regional influence is still apparent after the transform. This is due primarily to very large *in situ* chlorophyll values on continental shelves or high latitudes influencing low pelagic concentrations. We prevent this occurrence by explicitly defining 3 chlorophyll biomass domains: high chlorophyll domains, equatorial upwelling, and low chlorophyll ocean gyres. We find that a biomass threshold of 0.15 mg m^{-3} distinguishes the major functional oceanic domains of gyre vs. non-gyre in terms of chlorophyll (Domain 1). Further classification using a 0.07 mg m^{-3} threshold in the tropics produces a representation of equatorial upwelling domains (Domain 2). High chlorophyll regions dominating the high latitudes and coastal regions (depth < 200 m) are defined as Domain 3. The CZCS seasonal climatologies are first smoothed by averaging over 3 grid locations in longitude and latitude (i.e., a 3 x 3 grid point box comprising 9 total values). This reduces some of the variability within these domain characterizations, but additional tests are required to assure intra-domain coherence. The results exhibit a reasonable representation of high and low chlorophyll domains in the global ocean (Figure 2), where mid-ocean gyre domains of low chlorophyll are clearly distinguished from higher concentrations encountered in the polar and sub-polar domains, and equatorial upwelling domains are apparent. We additionally eliminate the Amazon/Orinoco plumes from the analysis (reverts to CZCS estimates) because of poor *in situ* sampling. These plumes are bio-geo-physically distinct from other domains [*Müller-Karger et al.*, 1988]. The plumes are defined as chlorophyll concentrations > 0.4 mg m^{-3} within a geographical range.

First the high chlorophyll and equatorial data are excluded (only data from Domain 1 are used), then the high chlorophyll domains are excluded from the analysis (only data from Domains 1 and 2 are used), and finally all data are blended regardless of regional definition (Figure 1). This produces three separately computed blended analysis products. The final blended chlorophyll analysis is produced by using the low chlorophyll blend in Domain 1 the equatorial blend in the tropics (Domain 2), and high chlorophyll data in Domain 3 (Figure 1). This method allows *in situ* values in high chlorophyll domains to affect other high chlorophyll regions in the final analysis, while preventing their influence into the low chlorophyll domains (e.g., the mid-ocean gyres), which is the main problem.

The effects of these methods are apparent in the sequence of blended analyses around the continental United States (Figure 3). When the blended analysis is performed using untransformed chlorophyll data with no domain restrictions, large coastal chlorophyll values on the Northeast US , Gulf of Mexico, and Gulf of California extend their influence well out into the open ocean. The size of the central Atlantic gyre is vastly reduced, and the entire Gulf of Mexico now has values >0.5 mg m^{-3} (Figure 3). The log-transform dramatically improves results by confining the influence of the large *in situ* coastal values to the inshore regions in the blended analysis, and recovering the original size, shape and magnitude of the central Atlantic gyre. Similarly, the Gulf of Mexico has receded to more realistic values in the central portion (<0.3 mg m^{-3}) with large values confined to the continental shelf. However, a problem remains near the Gulf of California, where large values near the Gulf (>1 mg $m^{-3)}$ continue to exhibit unrealistic influence beyond the continental shelf and into the Pacific Ocean (with typical values <0.1 mg m^{-3}). The domain restrictions prevent the excessive influence of the coastal data by not allowing extension of very large *in situ* coastal values into the low chlorophyll open ocean areas in the blended analysis. Note that the effects of the domain restrictions are generally small and only come into play in extreme circumstances.

Analysis of CZCS monthly data suggests that pigment may range over a factor of 2 in coincident points over the mission from year-to-year. This inter-annual variability can produce large discrepancies in *in situ* to satellite data match-ups. For example, suppose there exists only a single *in situ* observation in the tropical Pacific at 140°W at the equator, and that this observation occurred at the peak of the El-Niño in 1983. There are multiple observations in the CZCS at this location during its lifetime, so the CZCS climatology is only slightly affected by the 1982-1983 El-Niño. When we attempt to blend the *in situ* observation in to the chlorophyll climatology, there is a large discrepancy between the *in situ* and the CZCS observations,

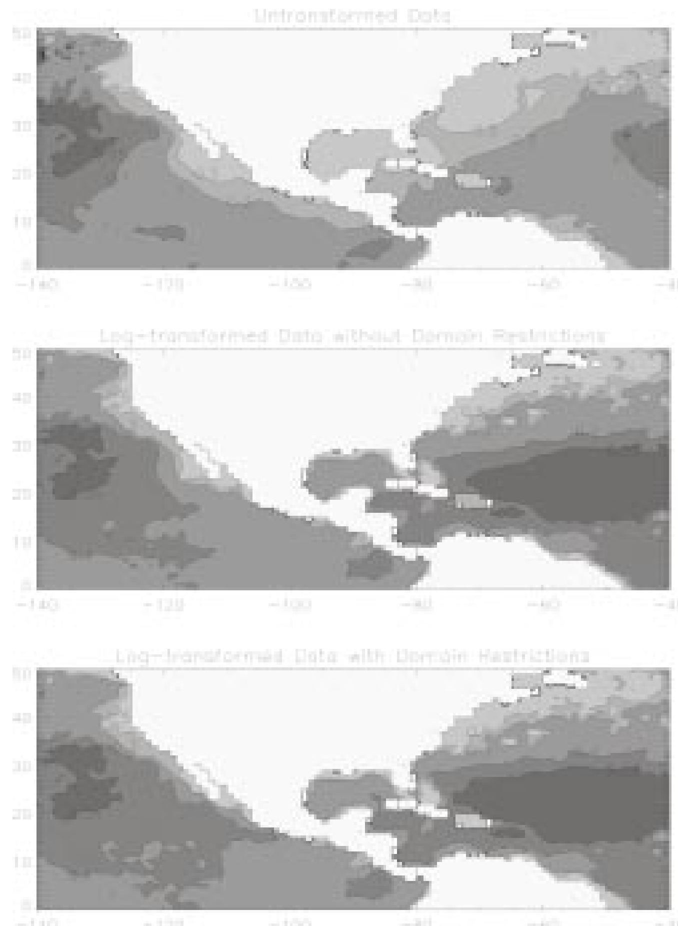

Figure 3. Illustration of the effects of the log-transform and domain restrictions on the blended analysis. A section of North America is depicted, with longitude labeled on the x-axis and latitude on the y-axis. Top: The blended analysis without log-transform and without domain restrictions. Middle: Blended analysis with transformed data but no restrictions on domain. Bottom: transformed data with domain restrictions.

producing a large bias correction. In 1983, however, there is little departure from CZCS observations and the *in situ* observation, so the bias correction distorts the blended analysis. To ameliorate this effect, we apply an inter-annual variability (IAV) correction to the blended analysis. Rather than apply *in situ* data as interior conditions in the seasonal climatology, we first evaluate *in situ*/satellite anomalies year-by-year in the seasonal data. These anomalies are averaged over the entire data record.

$$\log_{10} A(i) = \frac{S_y[\log_{10} I(i) - \log_{10} S(i)]}{n} \qquad (4)$$

where A represents the *in situ* - satellite anomaly at each grid point i, the summation is over years (y), and n is the number of years for which an anomaly is available (i.e., *in situ* and satellite data are coincident and co-located for a given year). Then *in situ* data are inserted into the seasonal climatology as anomalies from CZCS chlorophyll data.

$$\log_{10} C_{ibc}(i) = \log_{10} S(i) + \log_{10} A(i) \quad (5)$$

In the example above, the IAV correction identifies agreement between the *in situ* data and the CZCS in the 1983 El-Niño, and correctly produces a climatological blended field with little bias adjustment. A practical benefit of the IAV correction is that it can ameliorate the effects of sensor degradation in the CZCS lifetime [e.g., *Evans and Gordon*, 1994], by matching *in situ* observations with CZCS degradation state.

Because of sparse satellite and in situ chlorophyll data when matching co-located and coincident points, we adjust non-coincident *in situ* values by the mean IAV-correction of nearby coincident values. We limit the proximity to 10^o in longitude and latitude and exclude cross-regional values.

In the analysis of the method, we define twelve regions based on common geographical criteria, so that seasonal changes may be better evaluated. Boundaries of the geographical regions follow those used in the quality control of *in situ* data [*Conkright et al.*, 1994b, 1998]: Antarctic is defined as southward of 50^o S, the North Pacific and North Atlantic Oceans are northward of 40^o, and equatorial regions are bounded by –10^o and 10^o.

3. Results

3.1. In situ and CZCS Chlorophyll Data Sampling

The effort to blend *in situ* and CZCS chlorophyll data is hindered not only by the sparseness of *in situ* observations, but also by satellite observations. There are wide disparities in CZCS sampling from year-to-year (Figure 4), especially spring 1984 and summer 1983. The NODC *in situ* chlorophyll archive, by contrast, indicates rather uniform sampling between 1 and 3% of the total ocean consistently each season, for each of the 8 years of the CZCS lifetime. CZCS spatial coverage, however, dwarfs *in situ* sampling. *In situ* observations comprised between 10.0 and 10.8% of the 1^o by 1^o final blended data sets in each climatological season. Nevertheless, we consider this adequate for enhancing CZCS data by this method. *In situ* and CZCS samples are not uniformly distributed in space, so there are some under-sampled regions.

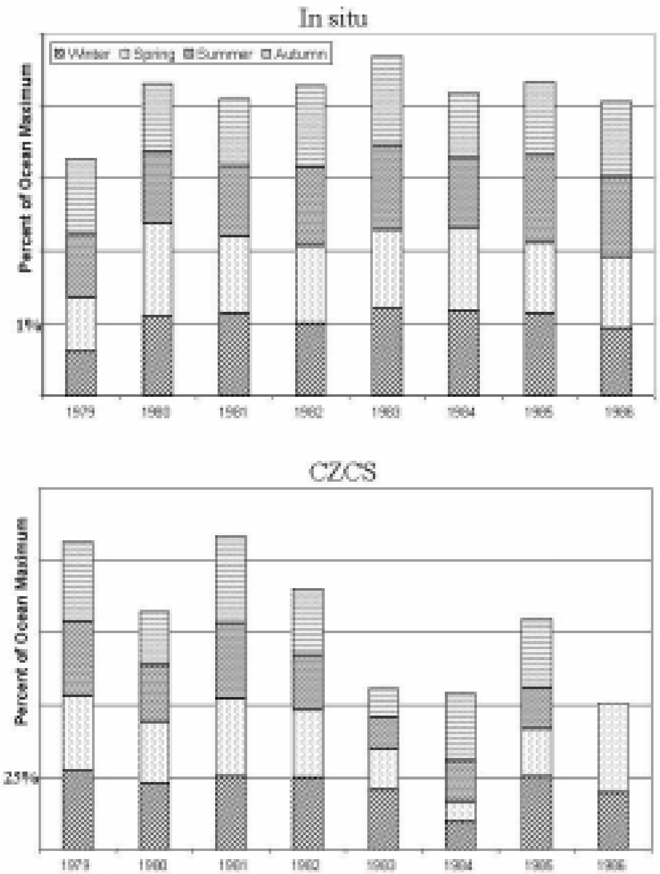

Figure 4. Spatial coverage by *in situ* (top) and CZCS (bottom) platforms for the years 1979-1986. A single ordinate tick-mark represents 1% of the global ocean for *in situ* data and 50% for CZCS data. *In situ* data provide 1-3% ocean coverage but are consistent for the 8-year period. These percentages refer to the amount of the global ocean that have samples within the 1^o-by-1^o spatial grids. CZCS data provide much larger spatial coverage (>50% in some seasons and years), but its limited duty cycle produces variable observational patterns.

3.2. Comparison of the Blended Chlorophyll Analysis and the CZCS Chlorophyll Estimates

Global blended chlorophyll concentrations are larger than CZCS estimates (Figure 5). The differences are dramatic in some seasons: spring global blended analysis exceeds CZCS estimates by 35% and summer by 17%. Winter and autumn differences are smaller, averaging about 8.5%. Furthermore, the seasonal pattern of chlorophyll appears to be different with the blended analysis, which exhibits a seasonal global peak for spring, in contrast to an autumn peak for the CZCS data. Both data sets indicate winter as the season of smallest global chlorophyll abundance.

Differences between the blended analysis and CZCS estimates are even more pronounced when considered within geographical regions. Regional differences, like the global analysis, are nearly always positive, suggesting an underestimation by the CZCS (Figure 6). The amounts can be large, often exceeding 20% and even >100% for the summer equatorial Indian Ocean. Negative anomalies (blended analysis < CZCS) are limited to the Northern Hemisphere and equatorial regions, and are usually smaller than the positive anomalies. Equatorial regions

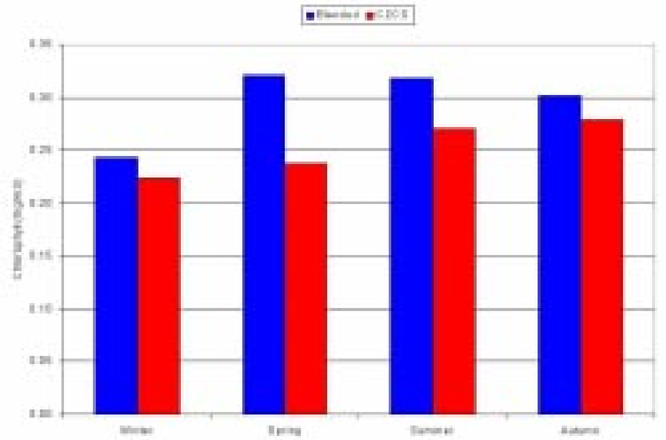

Figure 5. Global comparison between blended chlorophyll analysis and CZCS estimates by season (mg m^{-3}). The blended analysis produces globally larger chlorophyll concentrations, and changes the seasonal distribution. It exhibits a spring global maximum in contrast to the CZCS, which indicates an autumn maximum.

suggest large and persistent underestimation by the CZCS. For example, equatorial Pacific chlorophyll concentrations are typically 25-41% larger than CZCS estimates. Point-by-point analyses show that the root mean square (rms) difference between the blended chlorophyll analysis and the CZCS is 52-70% globally by season, and the rms between *in situ* and CZCS is about 82% for each season.

3.3. Global Distributions of Chlorophyll in the Blended Analysis

Application of the blended analysis for the CZCS years (1978-1986) shows that global scale patterns in chlorophyll are not substantially different from the CZCS (Figures 7-10). Seasonally, similar patterns of low chlorophyll concentrations in the mid-ocean gyres, high values in the high latitudes and coastal regions, and moderate values near the equator are apparent in both the CZCS data and the blended data sets. Considering that *in situ* values represent approximately 10% of the total data in the blended data sets, this suggests that the two data sets are in general agreement with respect to global spatial trends.

However, large regional and global differences between the blended analysis and CZCS estimates of chlorophyll are apparent at sub-region scales and are not evenly distributed. The global trend that the blended analysis produces generally larger estimates of chlorophyll than the CZCS holds, although there are exceptions. Some overall observations are 1) CZCS estimates of the eastern equatorial Pacific are consistently lower than *in situ* observations and the blended analysis in all seasons, 2) the Northeastern Pacific/Gulf of Alaska region is apparently systematically overestimated by the CZCS, while the Northwestern Pacific is underestimated, while the Sea of Okhostk and Sea of Japan are overestimated by the CZCS, 3) the Northeast US coast is apparently systematically underestimated by the CZCS, 4) the Patagonian shelf and South Atlantic portion of the subarctic transition zone are always underestimated, 5) the Mauritanian upwelling is larger in the CZCS estimates than in the blended analysis.

3.3.1. Winter

The distribution of *in situ* observations in winter is widespread and represents most of the geographical regions (Figure 7). There are gaps in CZCS coverage in the south central Pacific and in the northwest Pacific (Sea of Okhotsk) and Bering Sea.

The largest differences between the CZCS and blended analysis are in the Antarctic/sub-polar transition zone, especially in the Atlantic-Indian region, where the CZCS estimates are much lower than the blended analysis. An exception is the Scotian/Weddell Sea, where an abundance of *in situ* observations leads to a reduction in the analyzed chlorophyll. While the *in situ* values were high here in 1979 (> 0.5 mg m^{-3}), they were much lower than the CZCS observed that year. The result is barely noticeable in the blended analysis, but still contrasts with the increase in blended chlorophyll produced elsewhere in the region.

Australian and New Zealand coastal waters and the Tasman Sea exhibit much larger chlorophyll concentrations in the blended analysis, as does the tropical Pacific in general. These differences, plus minor differences in the south Pacific gyre, produce an enlargement of the equatorial upwelling area in the Pacific, and a reduction in the size of the south Pacific gyre.

A similar small increase in the chlorophyll concentrations of the North Pacific gyre is apparent in the blended analysis, although there appears to be no change in the gyre size. A dramatic difference is the lower chlorophyll estimates in the blended analysis in the northeastern Pacific and Gulf of Alaska coupled with the increased estimates in the northwestern Pacific. There is good *in situ* sampling in the northeastern portion, but there are few northwestern observations contributing to the increase. Good sampling in the Japan and East China Seas lead to reductions of chlorophyll in the blended analysis, and suggest the CZCS may overestimate here.

3.3.2. Spring

Spring is the season of the largest change between the blended analysis and the CZCS estimates. Changes are widespread (Figure 8), with vast areas of the oceans exhibiting positive anomalies (blended chlorophyll > CZCS). The extensive North Atlantic spring bloom routinely observed in CZCS data is even more pronounced and larger in the blended analysis. All three tropical regions show large positive anomalies, as does the southeastern Indian Ocean and the entire oceanic region near Australia and New Zealand. The North and South Atlantic gyres

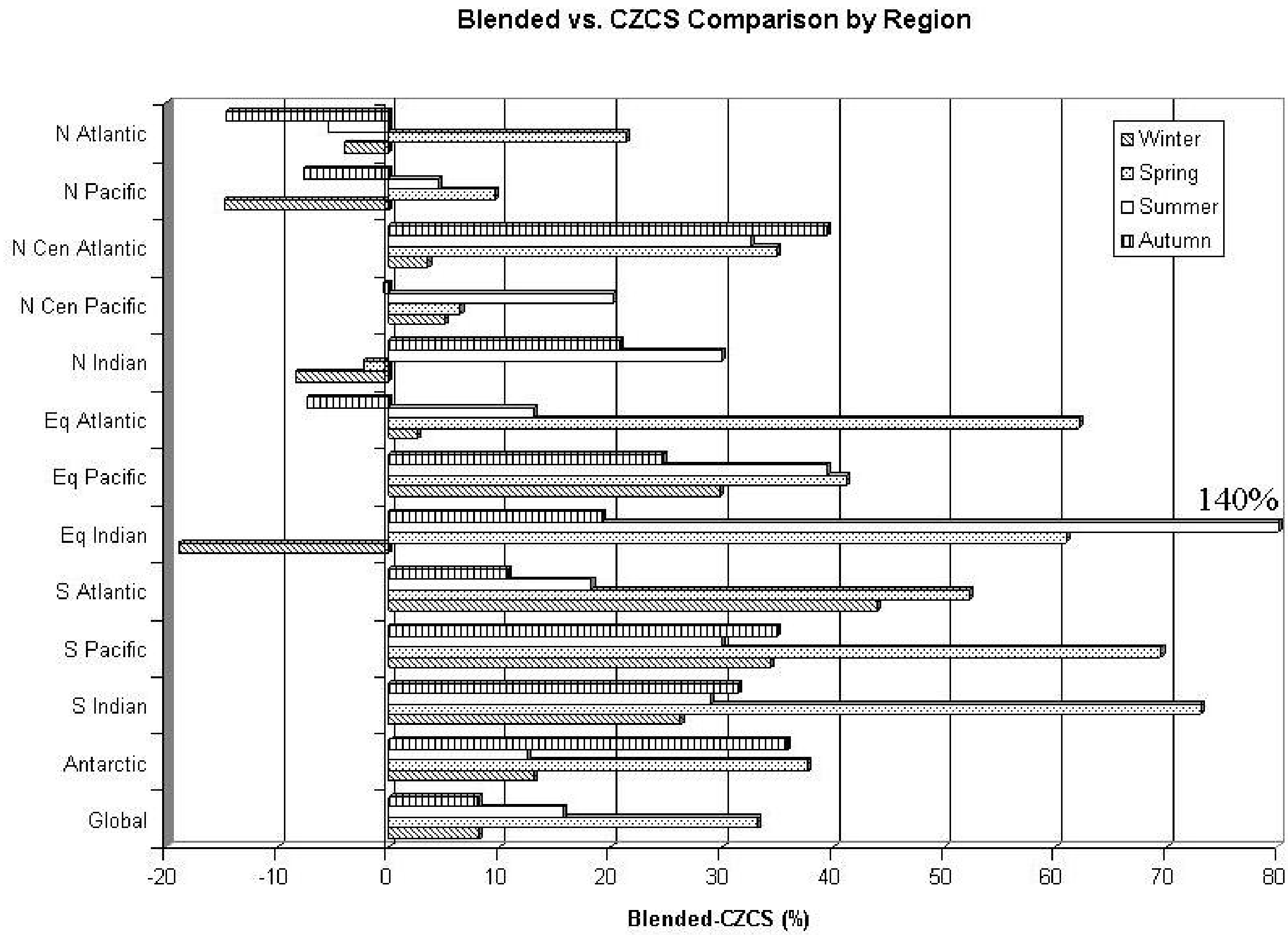

Figure 6. Regional comparison of chlorophyll estimated by the blended analysis and the CZCS, by season. Differences are expressed as blended - CZCS in percent (of CZCS)

have somewhat larger chlorophyll concentrations, and the North Atlantic gyre exhibits a substantial reduction in size. The northwestern Pacific has more *in situ* sampling in the spring than in the winter, and thus the positive anomaly here is better represented in the blended analysis. Poor *in situ* sampling in the Southern Hemisphere, coupled with discrepancies among the few samples, contributes to large anomalies. Some exceptions to the global positive anomaly trend are 1) extreme northwestern Pacific, Japan and Okhostk Seas, 2) northern Bering Sea, 3) northeastern Pacific, 4) Labrador Sea, 5) North Atlantic near Iceland, and 6) Mauritanian coast, which all exhibit negative anomalies.

3.3.3. Summer

The summer season exhibits some similarities between the blended analysis and the CZCS with the other seasons, such as negative anomalies in the northeast Pacific, Labrador Sea, Mauritanian coast, and seas near Japan, and positive anomalies in the tropical Pacific and Benguela upwelling regions, and US East Coast (Figure 9). But there are some important differences as well. One of the most important changes in the blended analysis is the representation of the southwest monsoon in the Arabian Sea. The structure of the chlorophyll patterns has changed in the blended analysis, such that the Somalian coast is diminished while the northern portion of the Arabian Sea is enhanced. There is extensive *in situ* sampling here. Other features are the large bloom near Sri Lanka and within the Bay of Bengal that appear to have been underestimated in the CZCS. Similarly, the blended analysis indicates larger chlorophyll concentrations south of Indonesia than the CZCS.

Poor sampling in the Southern Hemisphere is common to both *in situ* and satellite platforms in the summer season, except in the vicinity of Australia and New Zealand (Figure 9). Consequently, and because the samples appear to be in agreement, departures in the blended analysis from the CZCS tend to be reduced here, except very close to the few *in situ* observations.

3.3.4. Autumn

Autumn, like winter, shows small overall changes from the CZCS in the blended analysis. Southern Hemisphere *in situ* sampling in autumn is much improved over spring

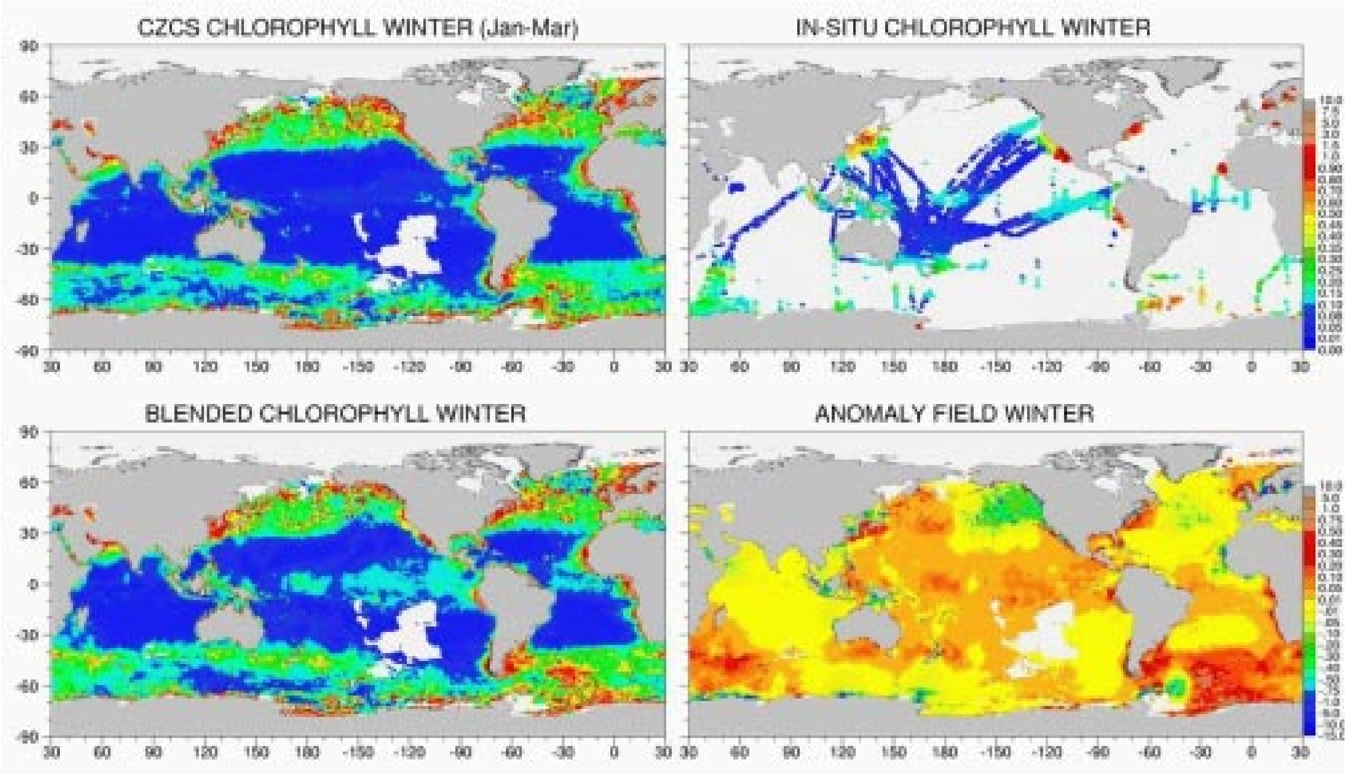

Figure 7. CZCS chlorophyll estimates, *in situ* observations, blended chlorophyll analysis, and anomaly (difference) fields for winter (January-March; mg m^{-3}). Anomaly indicates blended – CZCS. *In situ* observations have been expanded to enhance visibility. The color chart to the right of the *in situ* plot applies to the CZCS, *in situ*, and blended figures, and the anomaly field color chart is shown to the right of the anomaly field plot (in percent).

and summer, with the exception of the southwestern Indian Ocean (Figure 10). *In situ* sampling of the North and South Atlantic central gyres is sparse.

In autumn there are some similar patterns in the anomalies with the other seasons, such as the negative anomalies in the northeast Pacific and Okhostk, Japan, and East China Seas, positive anomalies in the tropical Pacific, and most of the US East Coast. But there are some striking differences as well. The eastern Australian/New Zealand area for the first time is lower in the blended analysis than in the CZCS, as is the northern portion of the Patagonian shelf. These changes arise in the presence of substantial *in situ* observations. Heavy *in situ* sampling in the southern Indian Ocean and nearby Antarctic Ocean, as well as the Drake Passage and the Scotian Sea give rise to large positive anomalies between the two chlorophyll estimates. The south-central Pacific gyre is noticeably reduced in size and contains larger chlorophyll concentrations in the blended analysis, and the northern Pacific gyre exhibits more spatial variability. This is due to the expansion of the equatorial upwelling in the blended analysis. The North Atlantic is somewhat reduced in chlorophyll biomass in the blended analysis, primarily due to *in situ* observations in disagreement with the CZCS near Nova Scotia and in the Norwegian and North Seas. The Arabian Sea contains much larger chlorophyll concentrations in the blended analysis

4. Discussion

Application of the blended analysis of *Reynolds* [1988] to chlorophyll climatologies using the CZCS and the NODC global chlorophyll archive produces major differences in the representation of global and regional chlorophyll distributions and magnitudes from that estimated by the CZCS alone. Seasonally, the differences vary between 8 and 35% globally, and are always positive anomalies (blended > CZCS). This suggests that the CZCS underestimates global chlorophyll concentrations. Although these estimates are within the error of the bio-optical algorithms used to convert the satellite-sensed radiances into estimates of chlorophyll [*Gordon et al.*, 1983], the results here suggest a bias. Furthermore, the results of the blended analysis suggest that the representation of chlorophyll is different seasonally and regionally. This can have major implications in the applications of CZCS data for primary production (e.g., *Iverson et al.*, 1999; *Behrenfeld and Falkowski*, 1997; *Antoine et al.*, 1996) and global biogeochemical cycles.

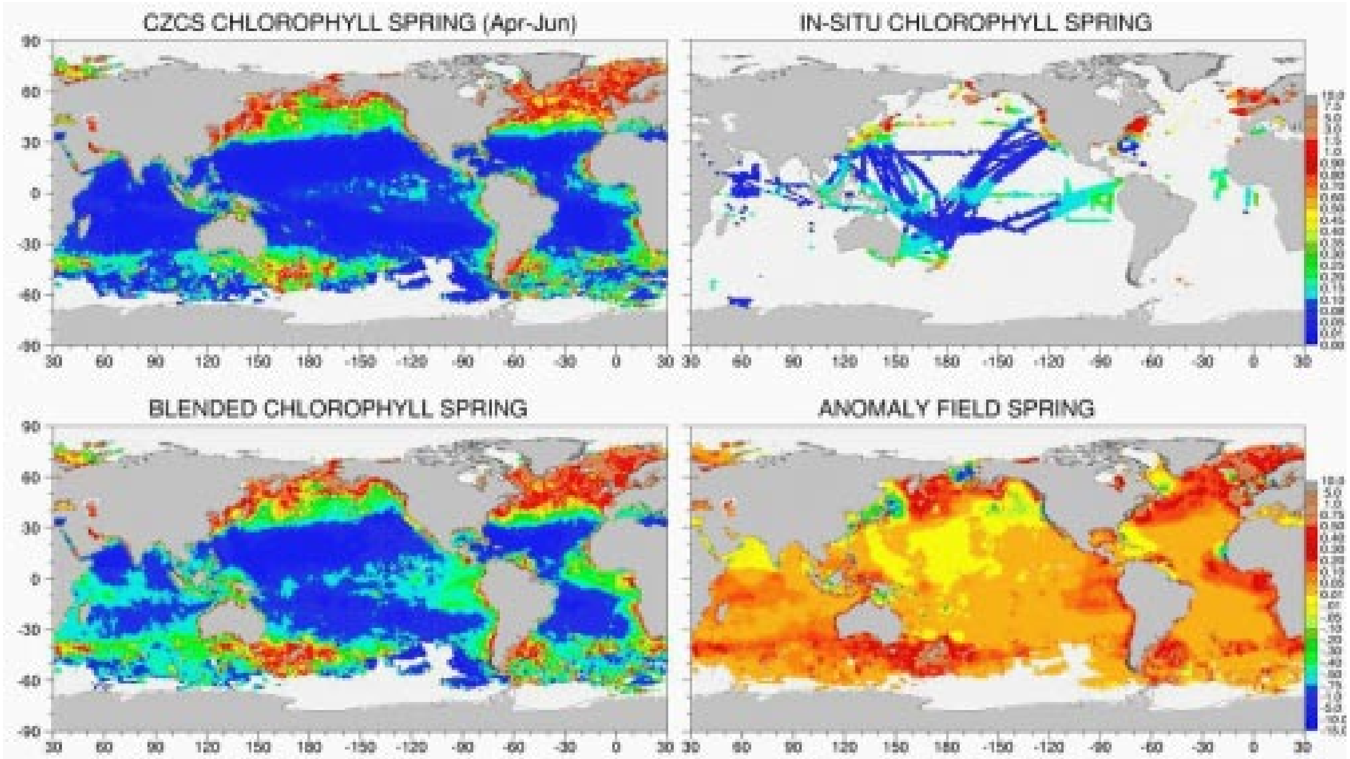

Figure 8. CZCS chlorophyll estimates, *in situ* observations, blended chlorophyll analysis, and anomaly (difference) fields for spring (April-June).

4.1. Blended Method

The primary purpose of the blended analysis is to remove biases in the satellite estimates [*Reynolds and Smith*, 1994] while retaining the spatial variability of the satellite data modified by the higher accuracy of *in situ* data. In a sense, the blended analysis uses the satellite field as an interpolation function for *in situ* observations. The method has been shown to achieve the objectives in application to SST analyses [*Reynolds et al*., 1989]. Ocean chlorophyll applications require modification of this method, primarily because chlorophyll is distributed in the oceans differently than temperature, but also because of vastly reduced sampling. These reasons have led to our system of constraints in application of the blended methodology, i.e., log-transforms to reduce the effects deriving from the extreme data range, and definition of biomass domains to prevent unrealistic cross-domain influence of *in situ* observations.

Most of the problems are eliminated by the log-transformation, as illustrated in Figure 3. However, the biomass domain restrictions are also important, in that they derive from the specific capabilities and deficiencies of remote ocean color sensors in general and the CZCS data set in particular. Calibration is one source of error that exhibits itself non-regionally, but it is only one of many issues for ocean color and the CZCS. Others include Case 2 waters [*Morel and Prieur*, 1977], improper characterization of the prevailing aerosol, high latitude errors associated with large solar zenith angles, and optically diverse phytoplankton compositions and associated detrital material that confound the bio-optical algorithms used to convert the satellite signal to chlorophyll. Many of these are in some way related to the biomass. For example, detrital material tends to be more prevalent in low chlorophyll concentrations [*Gordon et al*., 1988]. Some of them, while not directly related to biomass, tend to occur coincident with biomass definitions, e.g., large solar zenith angles associated with large biomass polar regions, or continental aerosol types often located in high chlorophyll coastal areas. By separating functional domains, we attempt to construct an overall enhanced blended data set that accounts for satellite deficiencies while preventing the bias correction of the blended analysis from extending into domains in which different satellite biases are expected. The separation used here is most important for the open ocean gyres, since they are very sensitive to the blended analysis. Our method enforces the criterion that gyres must be sampled to be affected by blending. We prefer to tolerate lack of bias correction in the central gyres, which represent as close to ideal remote sensing conditions as exist for ocean color applications (co-varying detrital components, low and steady chlorophyll concentrations, marine aerosol predominance).

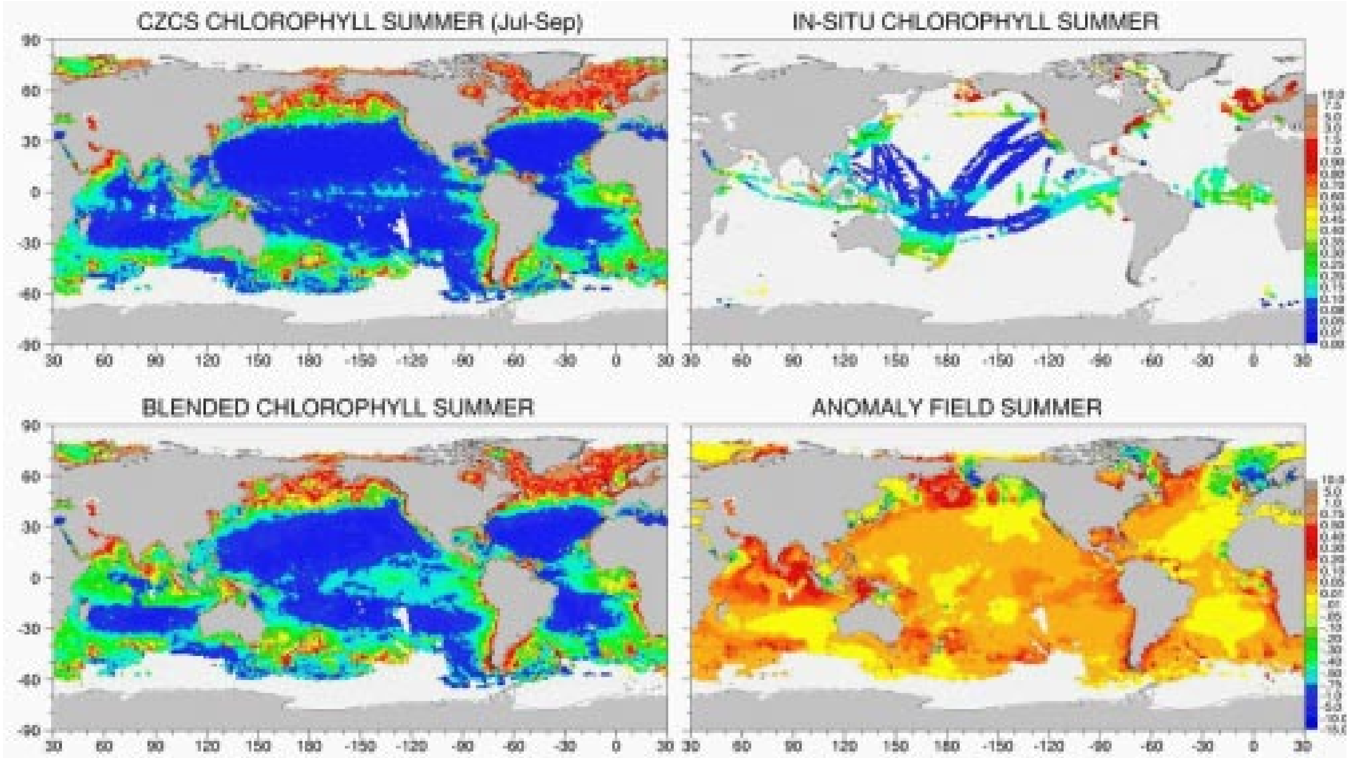

Figure 9. CZCS chlorophyll estimates, *in situ* observations, blended chlorophyll analysis, and anomaly (difference) fields for summer (July-September).

4.2. Differences in Distribution Between the Blended Chlorophyll Analysis and the CZCS Estimates

In situ and CZCS sampling sparseness is an important contributor to the differences in the global representation of chlorophyll between the blended analysis and the CZCS. However, deficiencies in the CZCS sensor design and/or shortcomings in the processing algorithms appear to produce most of the disagreements between satellite and *in situ* observations in the overall blended analysis. We assume *a priori* that *in situ* observations are without error, which we recognize as naive, but in the context of the satellite problems must be considered minor, especially after rigorous quality control.

Several of the deficiencies of the CZCS data can lead to underestimates of chlorophyll, as is generally observed in the blended analysis. Pervasive is the specification of a constant aerosol type (marine aerosol), which is necessitated in CZCS processing algorithms due to the absence of bands in the near-infrared to enable characterization of aerosol types without supervision. Although dominant over the oceans, marine aerosols tend to represent scattering and absorption properties at one end of the range of global aerosols, rather than the mean. Marine aerosols are large, non-spectral scatterers with little absorption. Most other aerosol types, i.e., those originating from land sources, are smaller and have a spectral scattering dependence, and are occasionally absorbing. The scattering dependence of continental aerosols produces larger optical thickness in the blue region of the solar spectrum than in the red. By specifying a non-spectral aerosol response, the CZCS processing algorithms produce excess blue radiance in the presence of continental aerosols. Since the bio-optical algorithms used to compute chlorophyll are inverse to the amount of blue radiance, the presence of these aerosols produces an underestimate of chlorophyll. *Monger et al.* [1997] found this to be a significant contributor to CZCS underestimates observed in the tropical Atlantic.

Limited sampling by the CZCS can also produce a bias. If persistent cloud cover precludes sampling during times of phytoplankton growth and abundance, the seasonal estimates produced by the CZCS can be too small. *Müller-Karger et al.* [1990] and *Mitchell et al.* [1991] found this situation in the Bering and Barents Seas, respectively. Persistent cloud cover also impacts tropical regions, as a result of the Inter-Tropical Convergence Zone (ITCZ). Coupled with especially large losses due to the presence of sun glint, sampling aliases in these areas can be important and can produce a bias.

Case 2 waters, where optically-active suspended or dissolved materials are present and do not co-vary with chlorophyll, can produce different effects on the CZCS estimates of chlorophyll. Larger than normal CDOM concentrations clearly produce an overestimate of chlorophyll, since they absorb strongly at 443 nm and less so at 520 nm and 550 nm. However, smaller-than-normal

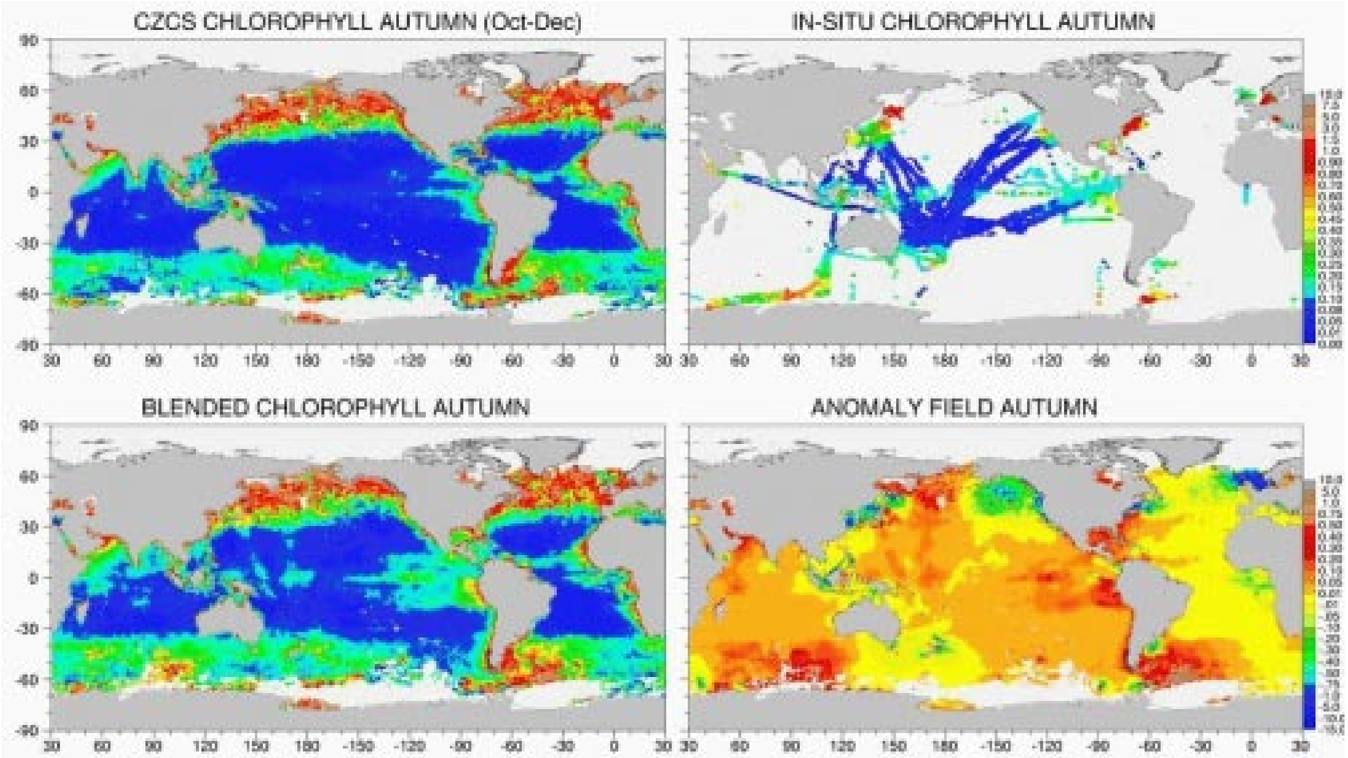

Figure 10. CZCS chlorophyll estimates, *in situ* observations, blended chlorophyll analysis, and anomaly (difference) fields for autumn (October-December).

amounts can produce the opposite effect. Upwelling areas may contain lower CDOM concentrations than expected by the CZCS bio-optical algorithms. *Thomas et al.* [1995] found one-third less DOM in the tropical Atlantic during the strong upwelling season than normal. *Monger et al.* [1997] attributed most of the CZCS underestimates they observed here to this effect. Suspended materials may have a more complex effect than CDOM. Since they scatter as well as absorb, they can produce an excessive water-leaving radiance signal at 670 nm, which the CZCS algorithms interpret as aerosol. More importantly, their effect on water-leaving radiance may be spectral, scattering more in the blue wavelengths like continental aerosols. This results in larger 443 nm radiance given the non-spectral assumption of the algorithm, and a resultant underestimate of chlorophyll.

Finally, sensor degradation over the lifetime of the CZCS appears to have caused underestimates of chlorophyll, mostly toward the end of the mission [*Evans and Gordon*, 1994]. *Hay et al.* [1993] measured water-leaving radiances in the Arabian Sea in May 1986 (very near the end of the CZCS) and found that the degradation algorithm used in the CZCS processing overestimated the radiance at 443 nm (but was reasonable at 520 and 550 nm). Again this overestimate can cause an underestimate of chlorophyll due to the inverse relationship between 443 nm radiance and chlorophyll in the CZCS pigment algorithm. These deficiencies are ameliorated by the IAV correction in the blended analysis.

4.3. Southern Hemisphere

Disagreement between *in situ* observations and CZCS estimates of chlorophyll is very large in the Antarctic Ocean. Expressed as root mean square, the differences are between 89% and 430% on a point-by-point comparison. The regional means reflect these disagreements in the autumn, which have a positive anomaly (blended > CZCS) of 36%, but in winter is only 13%. *Sullivan et al.* [1993] found that the CZCS underestimated pigment concentrations in the Southern Ocean by about up to 45%. Poor sampling in spring and summer preclude definitive regional analyses. Sampling by *in situ* platforms in the summer is at times actually better than the CZCS, resulting in addition of data to the summer blended fields. These non-coincident *in situ* observations provide insight into chlorophyll dynamics in the non-growing season when satellites are incapable of observing because of low light conditions.

The Antarctic Ocean presents many challenges to ocean color remote sensing, with typically large solar zenith angles that can exaggerate errors in the atmospheric correction algorithms. Furthermore, this is a region of very large spatial variability, where small mismatches in ship locations and satellite observations can be important. The phytoplankton species assemblages are quite different from those typically encountered in more temperate oceans, where the bio-optical algorithms were developed. *Mitchell and Holm-*

Hansen [1991] developed regional bio-optical algorithms to account for the reduced optical efficiency of the large phytoplankton species, such as *Phaeocystis* spp. and diatoms that dominate here [*Arrigo et al.*, 1999]. The Antarctic Ocean is also subject to persistent cloud cover, which obscures sampling by satellite and may result in biases [*Müller-Karger et al.*, 1990; *Mitchell et al.*, 1991]. A noteworthy difference between the data estimates is the ribbon of high chlorophyll in the CZCS at the margin of the Antarctic coast, extending from about 30^o E to the Ross Sea. This is greatly reduced by *in situ* observations and consequently the blended analysis, suggesting that it is ice mis-characterized as chlorophyll by the CZCS.

The southern Atlantic, Indian, and Pacific oceans all exhibit large positive anomalies in chlorophyll in the blended analysis relative to the CZCS data. This is true for all seasons. *In situ* sampling of the South Atlantic is very poor in every season but winter. However, the South Indian and South Pacific are sampled relatively well, except the South Indian Ocean in summer. *In situ* sampling sparseness must be considered when attempting to assess the performance of the blended analysis in these regions. Because of our method of constraints, the South Atlantic gyre tends not to be affected by the blended analysis, and most of the anomaly shown for the South Atlantic geographical region is driven by changes in the sub-arctic transition zone between 30^o and 50^o S. Recent studies have suggested a predominance of coccolithophores in this region in some seasons [*Eynaud et al.*, 1999]. These organisms can confound the remote sensing signal, by scattering light at 550 nm and 670 nm where the aerosols are characterized. The 550 nm band is also crucial for the bio-optical algorithms for the CZCS, and detached coccoliths associated with the coccolithophores can severely impact the water-leaving radiance signal *[Balch et al.*, 1989; *Brown and Yoder,* 1994; *Ackleson et al.*, 1994].

The southern Pacific Ocean has the heaviest *in situ* sampling of the entire Southern Hemisphere, due in large measure to the SURTROPAC program of the Centre ORSTOM de Nouméa [*Dandonneau*, 1986]. Generally, the *in situ* and CZCS observations are in quite good agreement in the open ocean gyres. Anomalies are modest in magnitude, and gyre size reduction in the blended analysis in summer and autumn is due to the expansion of the equatorial Pacific in the blended analysis. The western South Pacific, near Australia and New Zealand, is also heavily sampled in all four seasons by *in situ* platforms, but exhibits large anomalies in the blended analysis relative to the CZCS. These anomalies are usually positive but are negative in autumn. The positive anomalies are largest in spring, especially around New Zealand, where they exceed 0.5 mg m^{-3}. The heavy *in situ* sampling suggests these changes are representative.

4.4. Tropics

The tropical Pacific Ocean exhibits consistent and large positive anomalies. Considering the relatively heavy *in situ* sampling, this suggests the CZCS substantially underestimates chlorophyll here. Positive anomalies are large, ranging from 25% in autumn to >40% in spring and summer. From a remote-sensing standpoint, this region seems to meet the assumptions of the processing algorithms: low chlorophyll, predominance of marine aerosols, species assemblages not atypical from those for which the bio-optical algorithms were developed. A possible explanation would be lower than expected concentrations of CDOM, which has been reported in the tropical Atlantic during the strongest upwelling season [*Thomas et al.*, 1995]. Analysis of cloud cover and cloud optical thickness from the International Satellite Cloud Climatology Project (ISCCP) indicate that this area is impacted by large and persistent cloud cover, especially in the spring and summer. This cloud cover is related to the ITCZ, and produces monthly mean values of 80% cloud fraction at times, and optical thickness exceeding 8, especially in spring and summer. Sun glint is an additional impediment to CZCS observations in this region. Although the CZCS tilted to avoid sun glint, often the tilt was not operated optimally, and furthermore the sun glint masking algorithms assume a global mean wind speed of 6 m s^{-1}. This is probably a somewhat excessive estimate, as we have found the global mean to be closer to about 4.75 m s^{-1} [*Gregg and Patt*, 1994], based on 6 years of data from the Fleet Numerical Oceanography Center (1983-1988). The combination of cloud obscuration and excessive sun glint masking leads to loss of sampling in this region, in addition to errors introduced as a result of processing sun glint contaminated data when the wind speeds exceed the assumed global mean. The net result appears to be a substantial underestimate of chlorophyll concentrations by the CZCS. If sampling loss results in a bias, the it suggests that there may be a great deal of growth occurring under cloudy skies.

The tropical Atlantic suffers from the same problems associated with clouds and sun glint as the tropical Pacific, but has additional difficulties for remote sensing as well. Two of these are the occurrence of a highly non-standard aerosol deriving from the Saharan Desert and terrigenous input of optically active suspended and dissolved materials from three major rivers, the Congo on the eastern side and the Amazon and Orinoco on the west. Saharan aerosols can be absorbing [*Carder et al.*, 1991], which confounds the atmospheric correction algorithms. Sometimes, especially in spring, the aerosols may be so thick that the atmospheric correction algorithms fail, and the region is not sampled. SeaWiFS global monthly mean data from April 1998 show extensive loss of data in this region due to algorithm failure. This probably explains the localized negative anomalies consistently observed off the coast of Mauritania in the Canary Current – blue-absorbing aerosols would produce an overestimate of chlorophyll in the CZCS. However, south of Saharan Desert the anomalies tend to be positive, especially in spring, when it exceeded 100%. This conforms to the patterns observed for the tropical Pacific.

Monger et al. [1997] found underestimates by the CZCS in the eastern tropical Atlantic, and also agreed that the underestimates are larger in spring/summer, during the time of maximum upwelling. The differences were >100% in some samples. They suggested that reduced levels of CDOM in the upwelled water are primarily responsible for the CZCS underestimates, by providing less CDOM than the bio-optical algorithms expect. Better agreement between in situ and CZCS chlorophyll was observed in autumn by *Monger et al*. [1997], when upwelling is not as intense, which agrees with our blended analysis.

The outflow from the Amazon and Orinoco Rivers on the western side of the tropical Atlantic Ocean is quite prominent in both the CZCS data and the blended analysis for spring through autumn. The main portion of the plumes is unaffected by the blended analysis by specification, due to lack of *in situ* sampling. The distal end appears to be enhanced by the blended analysis. These results agree with findings by *Müller-Karger et al.* [1989] of an underestimate by the CZCS here. Otherwise, an overestimate of chlorophyll by the CZCS would be expected in the main portion, due to the effects of CDOM. These rivers are large sources of terrigenous dissolved organic matter to the oceans [*McClain et al*., 1997].

The largest anomaly in the entire blended data set is the tropical and North Indian Oceans in the summer. The anomaly approached 140% in the tropical Indian. This is the season of the southwest monsoon, which brings with it intense wind (mean monthly speeds in excess of 10 m s^{-1} in August), and heavy cloud cover (exceeding 80%). Winds speeds are poorly treated in the CZCS data, with the effects of sun glint previously discussed but also foam/whitecap reflectance problems that are not accounted for in the algorithms. These factors, in addition to low CDOM upwelled waters, cloud obscuration, and sun glint are possible reasons for the large positive anomalies encountered here with the blended analysis. This is a heavily sampled region by *in situ* platforms, so the anomalies are unlikely to be due to sparseness. The results here suggest that the large chlorophyll concentrations detected by the CZCS in the tropical Indian Ocean, Arabian Sea, and Bay of Bengal during the southwest monsoon are even larger, as represented by the blended analysis. Interestingly, in winter, when the winds have diminished and the skies have cleared, the blended analysis suggests the CZCS overestimates here.

4.5. Northern Hemisphere

Overall, the blended analysis and the CZCS estimates are in better agreement in the Northern Hemisphere than in the rest of the world's oceans. Anomalies are often <10% regionally and are occasionally negative, especially in the North Pacific and Atlantic Oceans (>40^o N). *In situ* sampling of the North Pacific is generally good, as are the coastal zones of the North Atlantic, but the central Atlantic gyre is poorly sampled. This is in contrast to the CZCS, which has a high density of sampling in the North Atlantic in the eight years of operation.

A closer analysis suggests the agreement between the two estimates of chlorophyll is not always good. Particularly noticeable is the large and consistent positive anomaly in the US East Coast. Possible explanations are the presence of continental aerosols, and Case 2 waters with non-co-varying non-living optical constituents. In autumn the Mid-Atlantic Bight and Gulf of Maine reverse pattern and exhibit a negative anomaly, while the rest of the US East Coast holds the trend.

The spring bloom in the North Atlantic is dramatically represented in the CZCS estimates. As extensive and large as it is indicated in the CZCS data, the blended analysis suggests it is even more extensive with larger magnitude. The bloom extends southward in the blended analysis, resulting in a substantial contraction of the North Central Atlantic gyre.

When there are *in situ* samples in the Labrador Sea, in spring and summer, the blended analysis suggests the CZCS overestimates in these intensely cold waters. This is a similar occurrence in the cold seas in the western Pacific, namely the Japan and Okhostk seas. Both of these regions may be subject to considerable fog due to the cloud water temperatures which may preclude sampling when it is dense, in addition to obscuration by clouds. The net effect here may be obscuration during low growth periods, producing a sampling bias.

The blended analysis in the North Pacific as a whole shows relatively little change from CZCS estimates. However, this is due to compensation occurring in the eastern portion, where a negative anomaly exists, and the western portion, where there is a strong positive anomaly. These conditions appear to be independent of season. *English et al.* [1996] compared sea truth data at Ocean Weather Station P and concluded that the CZCS overestimates chlorophyll. Our results agree with that assessment, but only as a local phenomenon. The rest of the North Pacific in the blended analysis, except the northwestern seas, suggests that the CZCS underestimates.

The apparent systematic over- and underestimation of CZCS in the northeastern and northwestern Pacific, respectively, is perplexing. *English et al.* [1996] attribute the overestimation in the northeastern portion to cloud contamination and the effects of inadequate compensation for electronic overshoot [*Mueller*, 1988]. Analysis of ISCCP cloud cover, optical thickness, and cloud water path does appear to indicate denser clouds in the eastern portion of the North Pacific, where optical thickness of 8-12 is not uncommon along with cloud water paths exceeding 100 g m^{-2}. These are contrasted with typical optical thickness of 4 or less in the western portion and cloud water paths generally between 50 and 100 g m^{-2}. However, no meridional trend could be detected in cloud cover. Both sub-regions are impacted by persistently large cloud cover, typically 80% or more. With the electronic overshoot problems of the CZCS [*Mueller*, 1988], cloud thickness can have important effects. Coupled with few cloud-free opportunities to view the surface, these problems may be more severe in the eastern portion. This may be consistent with the net effect of cloud contamination/electronic overshoot to produce an overestimate in the CZCS data, as suggested by *English et al.* [1996].

Several authors have noted CZCS underestimates in comparison to *in situ* data in the Northern Hemisphere. *Müller-Karger et al.* [1990] and *Mitchell et al.* [1990] attributed the problem to clouds, preventing sampling of times of large phytoplankton biomass. *Biggs and Müller-Karger* [1994] also noted understimation up to 85% by the CZCS in the Gulf of Mexico in November.

5. Conclusions

We have combined the extensive archive of NODC chlorophyll data (>130,000 profiles) with the global archive of the CZCS, using the blended analysis of *Reynolds* [1988] in an attempt to improve the quality and accuracy of global chlorophyll seasonal climatologies. The results indicate that the blended analysis produces a dramatically different representation of global, regional, and seasonal chlorophyll distributions than the CZCS. Generally, the CZCS appears to underestimate chlorophyll concentrations, globally by 8-35%, but on regional and seasonal scales that are much larger (the blended analysis is often 20-40% greater, and occasionally >100%). These observations agree with many independent regional comparisons in the literature. Occasional systematic overestimates occur in the northeast Pacific, the Mauritanian upwelling regions, and the northwestern Pacific Seas (Sea of Japan, Okhostk, and East China Seas). Upwelling zones in general appear to be underestimated by the CZCS, as compared to the blended analysis, particularly in the tropics. Regions and seasons of intensely large chlorophyll concentrations, such as the North Atlantic spring bloom and the southwest monsoon in the Arabian Sea, are much larger and more extensive in the blended analysis than in the CZCS. Large scale features, such as the size and shape of the mid-ocean gyres and tropical upwelling regions, change as a result of the blended analysis. These results could have large impacts on our assessments of global chlorophyll distribution, primary production, and biogeochemical cycling.

Application of the blended analysis for chlorophyll requires some modifications, due to the wide range of chlorophyll values encountered in the oceans and the sensitivity of various regions to *in situ* data sparseness. Our constraint modifications greatly alleviate some of the shortcomings of the method as applied to chlorophyll, but extreme data sparseness, such as the South Atlantic Ocean in particular, are still prone to difficulties.

Nevertheless, the widespread use of the global CZCS data set and significant advances in understanding that have resulted from this data set justify its use here. Furthermore, coupled with accurate *in situ* data, which form an interior "truth" boundary condition into which the spatial variability of the CZCS is merged using the conditional relaxation analysis method, provides a limited error-correction of the satellite data. Thus we can improve on the accuracy of the CZCS data while spatially extending the applicability of *in situ* data to produce an overall improved data set. Our objective here is to provide a climatological view of global and regional chlorophyll data using the best features of satellite and *in situ* sampling platforms. Despite limitations due primarily to *in situ* and somewhat satellite data sparseness, we believe this blended data set achieves this objective, and provides a more representative view of global seasonal climatological chlorophyll. Further improvement requires enhancement of CZCS data for new advances in radiative transfer methodologies, better calibration, etc., while simultaneously acquiring more *in situ* data. Application of this method to present and future satellites, such as SeaWiFS and the Moderate Resolution Imaging Spectrometer is entirely appropriate, but requires availability of simultaneous *in situ* data.

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